SCIENCE & TECHNOLOGY OFFICE

In Space and For Space Additive Manufacturing Initiatives at NASA Marshall Space Flight Center

2nd Symposium on Additive Manufacturing for Defense and Government

Washington, DC • May 13 – 14, 2015

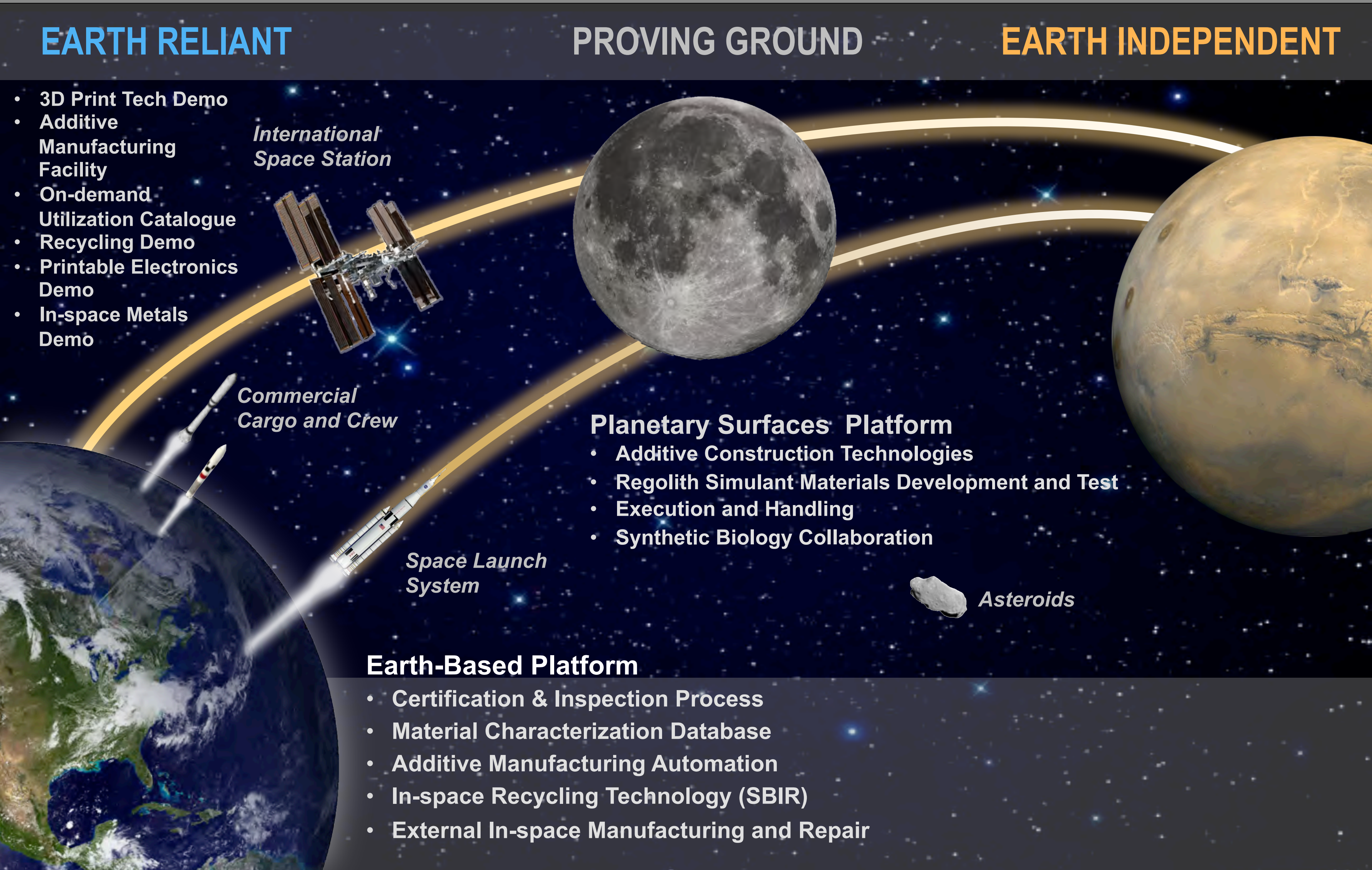
R. G. Clinton Jr., Deputy Manager

Science and Technology Office • NASA Marshall Space Flight Center

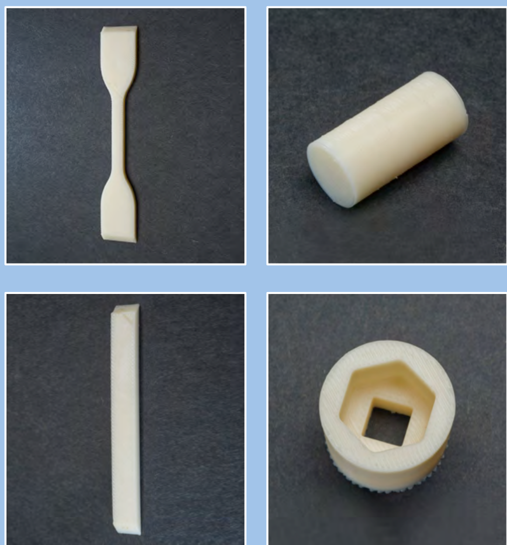
Agenda

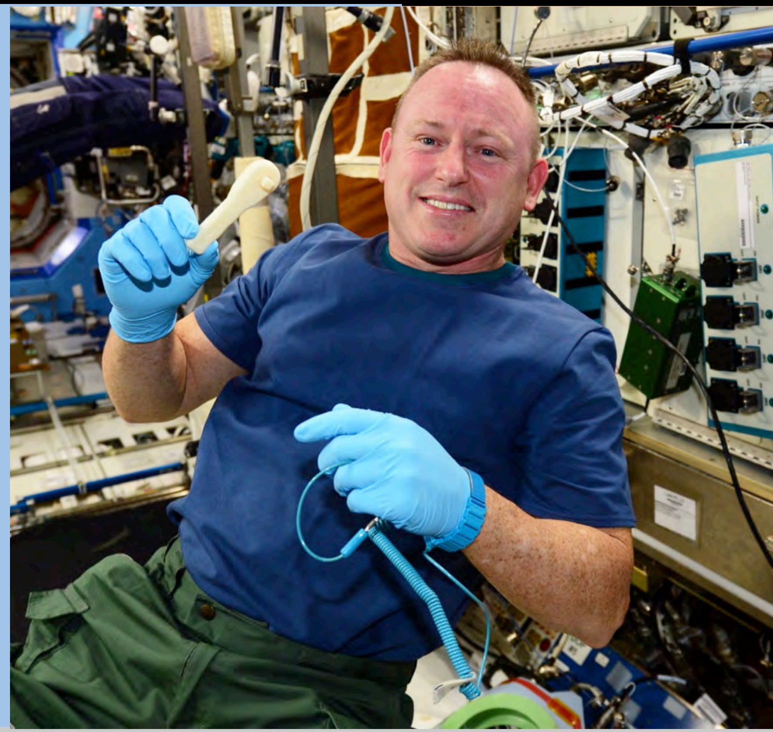
- In Space Manufacturing Initiative (ISM)
  - 3D Printer International Space Station Technology Demonstration
  - ISM Elements
  - ISM Roadmap
- For Space Manufacturing
  - Additive Manufacturing Demonstrator – Liquid Propulsion System
  - Draft Certification Approach
  - Addressing Foundational Knowledge Gaps
  - NASA/Air Force Additive Manufacturing Qualification and Certification for Space and Missile Applications Workshop
- Summary

Additive Manufacturing Path to Exploration



Mechanical Property Test Articles





Functional Tools

Printer Performance Capability

Text here?

In-Space Manufacturing (ISM)

- **3D Printer International Space Station Technology Demonstration**
  - The 3D Printer Technology Demonstration flight experiment launched on SpaceX-4 and was installed in the Microgravity Science Glovebox
  - Printed 21 engineering test from ABS feedstock. The printer functioned nominally.
  - 3D Print of a ratchet tool demonstrated on-demand capability by uplinking a part file that was not pre-loaded to the 3D Printer. *Part was designed, approved for uplink/printing, and printed on-orbit within a one week span.*
  - The first flight samples were received at MSFC on 3/17/15
  - Detailed testing and analyses to compare the flight articles to the ground control samples has begun. Results expected by Sept. 2015.

- **Future Engineers 3D Printing in Space Tool Challenge**
  - National challenge conducted jointly by NASA and American Society of Mechanical Engineers to design a tool that astronauts would need on ISS
  - Competition was held in two divisions, Junior and Teen
  - Robert Hillan, the national winner of the Challenge was introduced to Alabama Governor and Lt. Governor and was recognized on both the Alabama State House and Senate floors at MSFC Day in Montgomery.
  - Robert's part will be printed on ISS later this year.

3D Printer Installed in MSG on ISS

ISS Commander Butch Wilmore and 3D Printed Sample Container

Future Engineers Winning Part - MPMT

In-Space Manufacturing Elements

- **Material Characterization Database Development**
  - Objective: Characterize microgravity effects on printed parts and resulting mechanical properties Develop design-level database for microgravity applications.
  - MSFC team has performed initial characterization on ABS and ULTEM.
  - B-basis datasets received from RP+M for ULTEM through America Makes project
  - MSFC will generate B-basis property database from ground samples produced using the flight spare 3D printer.
  - Phase II operations for additional on-orbit prints of engineering test articles are being planned with ISS for later this year.
  - All datasets will be available through the MSFC Materials and Processes Technical Information System (MAPTIS)
- **On-demand ISM Utilization Catalogue Development**
  - Objective: Develop a catalogue of approved parts for in-space manufacturing and utilization.
  - Joint effort between MSFC AM materials and process experts and space system designers and JSC ISS Crew Tools Office
  - Parts being considered include crew tools, payload components, medical tools, exercise equipment replacement parts, cubesat components, etc.
  - First parts are in design and ground test process.

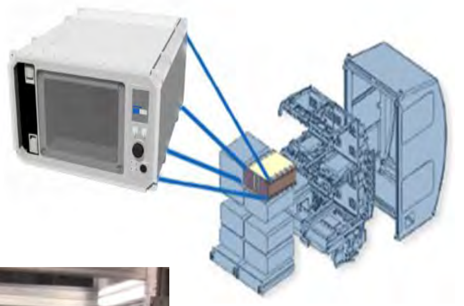
ISM Characterization of Materials and Process Variability (above)

Housekeeping Vacuum Crevice Tool

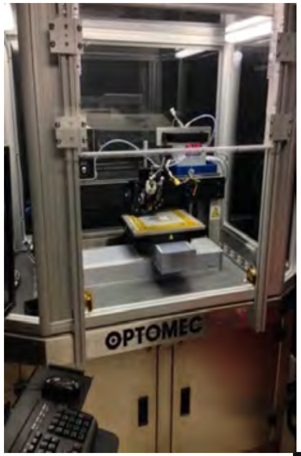
EVA Suit Fan Shipping Container: Design Clearances had to be relaxed for part to be printed on one FDM printer (red) vs. another in order for the parts to be assembled.

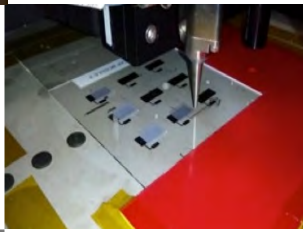
In-Space Manufacturing Elements

- **AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space**
  - Commercial printer for use on ISS
    - Incorporates lessons learned from 3D Printer ISS Tech Demo
    - Expanded materials capabilities: ABS, ULTEM, PEEK
    - Increased build volume
  - Anticipated launch late CY2015
- **In-space Printable Electronics Technology Development**
  - Collaborating with Xerox Palo Alto Research Center (PARC) on Printable Electronics technologies developed at MSFC and Xerox PARC.
  - Collaborating with NASA Ames Research Center printable electronics team.
  - Printable Electronics Roadmap developed targeting ISS technology demonstration.
- **In-space Multi-Material Manufacturing Technology Development**
  - In-space Adaptive Manufacturing (ISAM) project with Dynetics utilizing the Hyperbaric Pressure Laser Chemical Vapor Deposition (HP-LCVD)
  - HP-LCVD technology holds promise for a novel solution to manufacturing with multiple materials (including metallics) in microgravity.
  - Phase I deliverable is small spring similar to design utilized on ISS

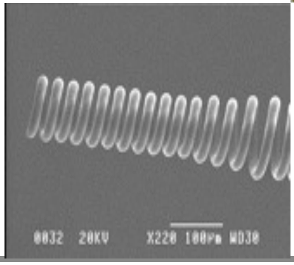


Additive Manufacturing Facility





Printable Electronic Technologies



Spring Created by Adaptive Manufacturing

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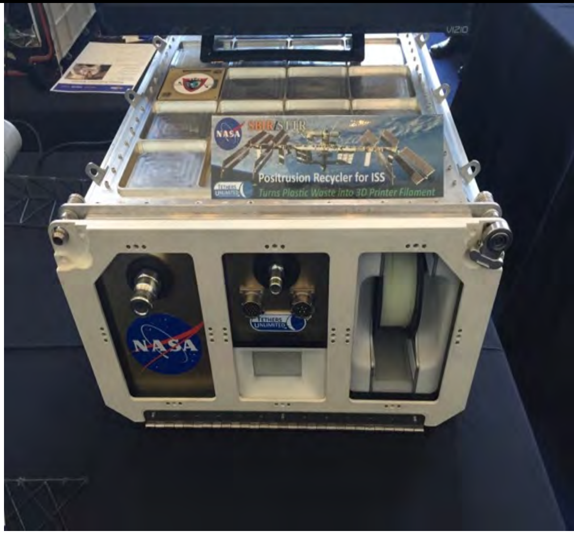
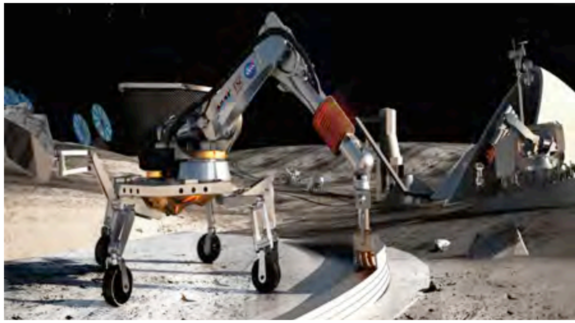
In Space Manufacturing Technology Infusion

- **In-space Recycler ISS Technology Demonstration Development (SBIR 2014)**
  - Objective: Recycle 3D printed parts into feedstock to help close logistics loop.
  - Phase I recycler developments completed by Made In Space and Tethers Unlimited.
  - Phase II SBIR (2014) awarded to Tethers
  - Final deliverable will result in flight hardware for the In-space Recycler for proposed ISS Technology Demonstration in FY2017.
- **Launch Packaging Recycling Phase I SBIR (2015)**
  - Objective: Recycle launch packaging materials into feedstock to help close logistics loop
- **ACME - Additive Construction by Mobile Emplacement (STMD GCD)**
  - Joint initiative with the U. S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) Automated Construction of Expeditionary Structures (ACES) Project
  - Objective: Develop a capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials and minimum number of personnel.
  - Goal: Produce half- scale and full-scale structures with integrated additive construction system at a lab or planetary analog site (September 2017)



Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo



Concept of ATHLETE-based autonomous additive construction system on extraterrestrial surface. Courtesy: B. Khoshnevis, CCI

In-space Manufacturing Technology Development Roadmap

Earth-based

Pre-2012

Ground & Parabolic centric:

- Multiple FDM Zero-G parabolic flights
- Trade/System Studies for Metals
- Ground-based Printable Electronics/ Spacecraft
- Verification & Certification Processes under development
- Materials Database
- Cubesat Design & Development

International Space Station

3D Print Tech Demo

2014

- **In-space:3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **AF/NASA Space-based Additive NRC Study**
- **ISRU Phase II SBIRs**
- **Ionic Liquids**
- **Printable Electronics**

Plastic Printing Demo

Add Mfctr. Facility

Recycler

SmallSats

Printable Electronics

Metal Printing

Self-repair/ replicate

External In-space Mfctr

2015 2016

- ***3D Print Tech Demo***
- ***Future Engineer Challenge***
- ***Utilization Catalogue***
- ***ISM Verification & Cert Process Development***
- ***Add. Mfctr. Facility (AMF)***
- ***In-space Recycler SBIR***
- ***In-space Material Database***
- ***External In-space 3D Printing***
- ***Autonomous Processes***
- ***Additive In-space Repair***

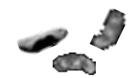
2017 2018

ISS: *Utilization/ Facility Focus*

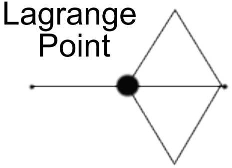
- In-space Recycler Demo
- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Printable Electronics Tech Demo
- Synthetic Biology Demo
- Metal Demo Options

Exploration

Asteroids

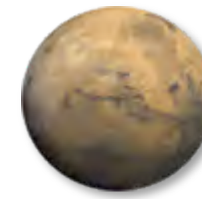


Lagrange Point



Lunar

Mars



2020-25

Lunar, Lagrange FabLabs

- Initial Robotic/ Remote Missions
- Provision some feedstock
- Evolve to utilizing in situ materials (natural resources, synthetic biology)
- Product: Ability to produce multiple spares, parts, tools, etc. “living off the land”
- Autonomous final milling to specification

2025

Planetary Surfaces Points Fab

- Transport vehicle and sites would need Fab capability
- Additive Construction

2030 - 40

Mars Multi-Material Fab Lab

- Utilize in situ resources for feedstock
- Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)
- Product: Fab Lab providing self-sustainment at remote destination

ISS Technology Demonstrations are Key in ‘Bridging’ Technology Development to Full Implementation of this Critical Exploration Technology.

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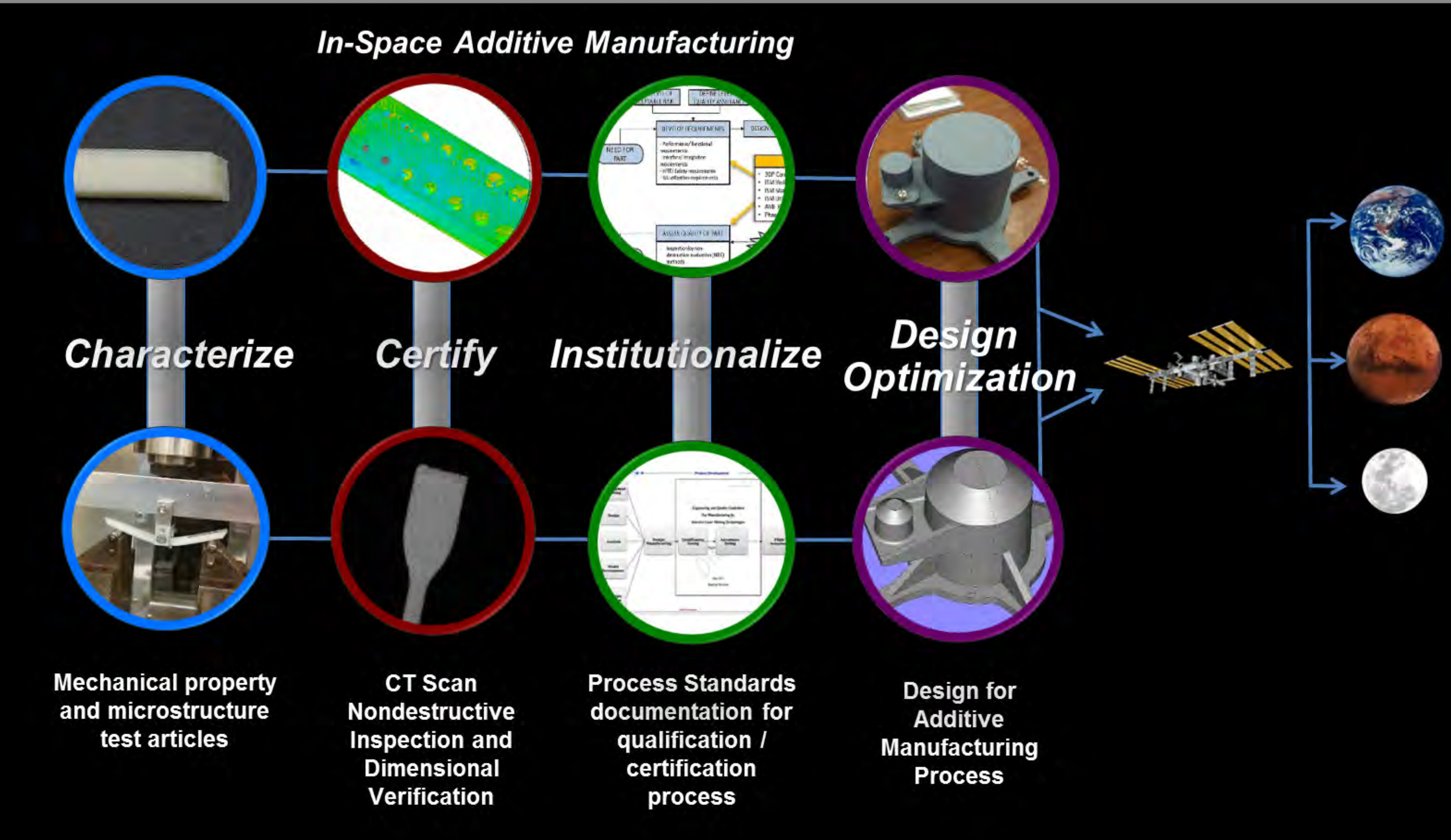
In-space



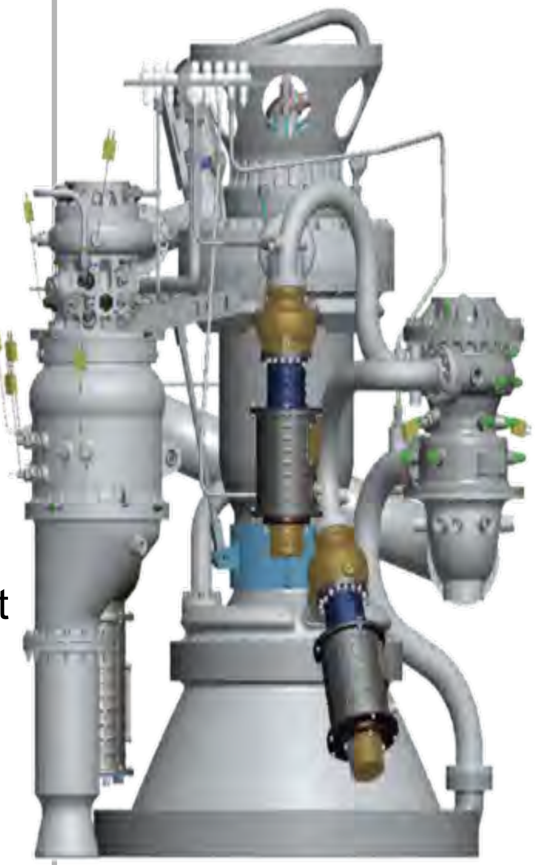
Characterize→ Certify→ Institutionalize→ Design for AM

Liquid Propulsion System (LPS): Demonstrating Additive Manufacturing and Transforming Liquid Engine DDT&E

Additive manufacturing related

Project Objectives

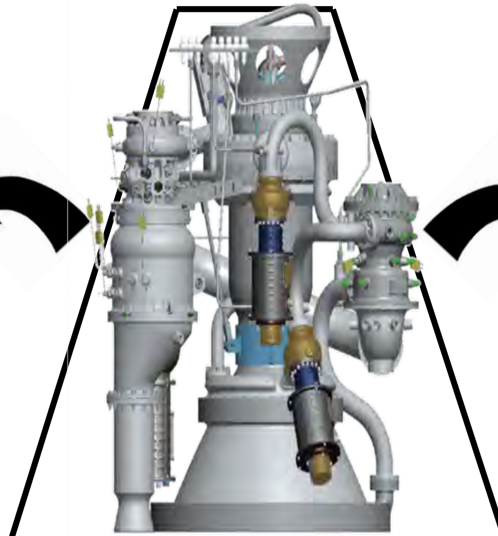
- Reduce the cost and schedule required for new engine development and demonstrate it through a complete development cycle.
  - Prototype engine in less than 2.5 years
  - Additive manufacturing to reduce part cost, fabrication time, and overall part count
  - Lean Development approach
    - Focus on fundamental/quick turn around analysis to reduce labor time and cost to get to first development unit
    - Get hardware into test fast so that test data can be used to influence/refine the design
- Advance the TRL of additive manufactured parts through component and engine testing
- Develop a cost effective prototype engine whose basic design can be used as the first development unit for an in space propulsion class engine.



Strategic Vision: Much Larger Than Any One Project or Organization

Defining the Development Philosophy of the Future

- Integrating Design with Manufacturing
- 3D Design Models and Simulations Increase Producibility
- Transforming Manual to Automated Manufacturing
- Dramatic Reduction in Design Development, Test and Evaluation (DDT&E) Cycles



Bridging the gap between the present and future projects that are coming

Building Experience "Smart Buyer" to enable Commercial Partners

Building Foundational Industrial Base

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Game Changing Aspects

State of the Art		Liquid Propulsion System (LPS)
• DDT&E Time – 7-10 years	***1/2 Dev Lead Time***	• LPS DDT&E Time – 2-4 years
• Hardware Lead Times – 3-6 Years	***1/6th Production Time***	• Hardware Lead Times – 6 Months
• Engine Cost – $20 - $50 Million	***1/10th Reoccurring Cost***	• LPS Engine Cost – $1-$5 Million
• Test-Fail-Fix Cycles – 150 – 300 which cost millions per cycle	***Low Cost Test-Fail-Fix Cycles***	• LPS Test-Fail-Fix Cycles – TBD but cost per cycle cheaper
• Engines Developments On Schedule or Cost – 0	***Once in A Lifetime***	• Engines Developments On Schedule or Cost – LPS on schedule
• Number of Engine Started and Not Finished – 7 (MC-1, COBRA, RLX, RS-83, RS-84, X-33, J-2X)	***Once in A Lifetime***	
• In House Team – Not since 1990's drove Merlin and J-2X	***Trained PM/CE's***	• In House Team – LPS
• NASA PM and Insight – 30-50 FTE		• LPS Management – LSE Model

Hardware and Testing Accomplishments

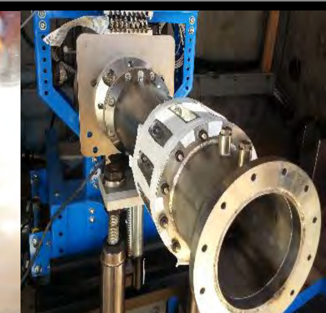
Caption

MCC Liner

Laser

Main Fuel Valve Cryo Test

Full Scale Injector Water Flow



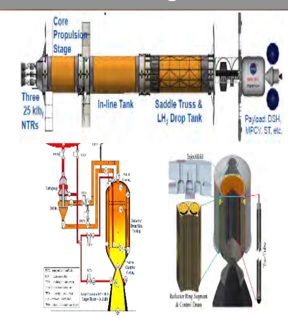
Turbine Test Rig

Sub-scale Injector Test

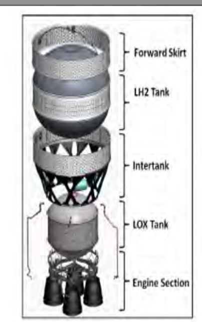
Advanced Manufacturing Demonstrator (AMD)

Investment directly benefits prototype engine development and indirectly enables and facilitates technology across multiple current and future activities for NASA and industry.

Methane Lander



Nuclear Thermal Propulsion (NTP)



Exploration Upper Stage (EUS)

Additive Manufacturing Certification for Rocket Engines

- **Opportunity**
  - Additive Manufacturing (AM) offers revolutionary opportunities in mechanical design innovation, system performance, cost savings, and schedule reduction

- **Risk**
  - Process sensitivity :: unknown failure modes
  - Lack of governing requirements
  - Rapidly evolving technology
  - Too easy, too cheap = ubiquitous, lack of rigor
  - AM related failure tarnishes the technology

- **Requirement choices dictate how we embrace, foster, and protect the technology and its opportunities wisely**

Requirements Approach

- **Typical scenario used to control critical processes**
  - Broad Agency-level standards provide requirements
    - NASA-STD-6016 Materials
    - NASA-STD-5012 Propulsion Structures
    - NASA-STD-5019 Fracture Control
  - *Which call* process or quality standard controls product, for example:
    - AWS D17.1 Fusion Welding for Aerospace Applications
    - SAE AMS 2175 Classification and Inspection of Castings
    - SAE AMS 4985 Ti-6-4 Investment Castings
  - *Which call* considerable collections of “Applicable Documents”
- **Additive manufacturing standards currently very limited**
  - Lacking standardization is a universal, industry-wide issue, not just NASA
  - Mainly ASTM, Committee F42 on Additive Manufacturing
    - F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718)with Powder Bed Fusion
    - F2924 for Ti-6-4, F3001 for Ti-6-4ELI, F3056 for In625
  - Other Standards organizations in planning
    - SAE AMS, AWS
- **NASA required to develop government requirements to balance AM opportunities and risks.**

NASA Approach to AM Requirements

Develop a Center-level (MSFC) requirement

- Allows for more timely release (targeting May 2015)
- Review circle much wider than common
  - Centers
  - NESC (materials, structures, NDE, Reliability)
  - Partners (Aerojet-Rocketdyne, SpaceX, Lockheed Martin)
  - Industry (GE, Honeywell)
  - Certifying Agencies (FAA, USAF)

Key topics in the draft AM requirements

- ***Tailoring***
- Governing standards
- AM Design
- ***Part Classification***
- Structural Assessment
- Fracture Control
- Qualification Testing
- ***Part Development Plans***
- ***Process Controls***
- ***Material Properties***
- Finishing, Cleaning, Repair Allowances
- Part Inspection and Acceptance

Tailoring and Part Classification

- **Tailoring and Part Classification provide flexibility within the requirements**
  - Tailoring
    - Document targets succinct, high-level requirement statements
    - Considerable commentary on intent
    - Allows for user tailoring to intent
  - Classification
    - All AM parts are placed into a simple risk-based classification system to help customize requirements according to risk
    - Three decision levels
      - Consequence of failure (High/Low) {Catastrophic or not}
      - Structural Margin (High/Low) {strength, HCF, LCF, fracture}
      - AM Risk (High/Low) {build complexity, access, inspectability}
    - Part classification highly informative relative to part risk.

Part Development Plans

- **Part Development Plans (PDPs) document the implementation and interpretation of the requirements for each AM part**
  - Content varies with part classification
  - Example Content:
    - Part classification and rationale
    - Witness sampling requirements and acceptance criteria
    - First article evaluations and re-sampling periods
    - Build orientation, platform material, and layout
    - Repair allowance, Inspection requirements, critical dimensions

Process Controls

- **Four types of process control are levied**
  - Metallurgical Process
  - Part Process
  - Equipment Process
  - Vendor Process
- **Each process requires qualifications or certifications**

Material Properties

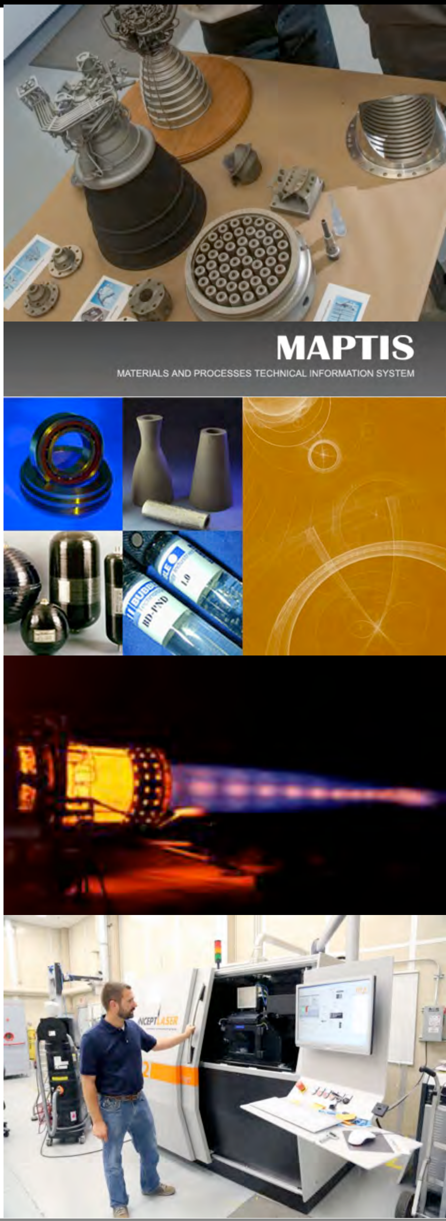
- Material properties often confused with certification
  - Certification >> material properties
- Highly “localized user” process requires different thinking
- Shift emphasis away from exhaustive, up-front material allowables intended to account for all process variability
- Move toward ongoing process monitoring with thorough, intelligent witness sampling of each build
- Hybrid of Statistical Process Control and CMH-17 approach for process-sensitive composite material equivalency
- Utilize a QMP to develop a *Process Control Reference Distribution* (PCRD) of material properties that reflects not the design values, but the actual mean and variability associated with the controlled AM process
- Enforce suite of design values compatible with PCRDs
- Accept parts based on comparison to PCRD, not design values
- PCRDs are continuously updated, design suite must be monitored and determined judiciously early on
- Allows for adoption of new processes without invalidating large allowables investments

Key Knowledge Gaps and Risks

- **Available requirements will not mitigate AM part risk to an equivalent level as other processes for some time to come!**
- **Known Unknowns needing investment:**
  - Unknown failure modes :: limited process history
  - Open loop process, needs closure or meaningful feedback
  - Feedstock specifications and controls
  - Thermal processing
  - Process parameter sensitivity
  - Mechanical properties
  - Part Cleaning
  - Welding of AM materials
  - AM Surface improvement strategies
  - NDE of complex AM parts
  - Electronic model data controls
  - Equipment faults, modes of failure
  - Machine calibration / maintenance
  - Vendor quality approvals

Knowledge gaps exist in the basic understanding of AM Materials and Processes, creating potential for risk to certification of critical AM Hardware.

AMSII Project Goal & Objectives



Goal

- Develop powder bed fusion (PBF) as a reliable and routine alternative to traditional manufacturing methods for human-rated flight hardware.

Objectives

- Mature a jointly-defined, resource-loaded technology project to close the knowledge gaps that underpin our drafted AM requirement document.
  - Effort not to exceed 3 years, $10M.
  - Emphasis on activities required for flight certification.
  - Initial focus on Inconel 718 produced with powder bed fusion technology.
- Develop an inter-center team to pool knowledge and provide peer review of AM technology development and activities.
- Mature NASA-wide or local requirement document(s) in order to enhance standardization of AM for flight hardware.

Center Roles and Technical Objectives

Lead Center in Blue

Build the standard level of information on AM powder bed fusion processes that is required for certification of any new critical process used for aerospace applications. Better understanding of controlling process parameters and process failure modes will be achieved through completion of this study.

- Certification Requirements – **MSFC**/JSC/KSC (committee) **Objective**: Develop an Agency-wide accepted practice for the certification of AM processes for aerospace hardware.

1. Powder Influence – **GRC**/LaRC/MSFC **Objective**: Understand how basic powder feedstock characteristics influence a PBF part's physical, mechanical, and surface properties.
2. Build Interactions – **MSFC**/GRC/JSC/KSC/LaRC **Objective**: Use DOEs to understand how basic AM build factors influence part properties. (Answers how we declare the PBF process acceptable & in-control; e.g. microstructural criteria, density criteria, laser/power effects, process FMEA, mitigation of process failure modes)
3. Characteristic Defects – **LaRC**/GRC/JSC/KSC/MSFC **Objective**: Identify, catalog, and reproduce defects characteristic of the AM process.
4. Thermal Processing – **GRC**/LaRC/MSFC **Objective**: Establish an understanding of how post-build thermal treatments affect build quality, microstructural evolution, and mechanical properties.
5. Surface Improvement – **LaRC**/MSFC **Objective**: Understand how as-built and improved AM surface texture influence part performance and fatigue life.
6. Characterization in Environment – **MSFC**/GRC/KSC/JSC/LaRC **Objective**: Understand mechanical behavior of AM Inconel 718 in representative aerospace environments.

Related Task: NASA NDE Working Group Additive Manufacturing Proposed Tasks – Various Centers **Objective**: Assessment of NDE Capability for AM parts and creation of NDE standards and models. (sponsored by OSMA)

Related Task: Process Modeling – ARC/GRC/MSFC **Objective**: Determine Global Energy Input parameter as function of build factors. Validate model against test data from different AM machine systems. (to be proposed)

Project designed to leverage Centers' critical skills, knowledge, and expertise.

Time	NSMMS Tutorials & Workshop Agenda (6/23/2015)	
0800 - 0930	**Keynote: Jason Crusan, Director Advanced Exploration Systems, NASA** **"Pioneering Space: Working to be Earth Independent"**	
0930 - 0935	**Additive Manufacturing Qualification and Certification for Space and Missile Applications Workshop**	
0935 - 1035	**Overall Certification Process** Government Agencies	1. Rick Russell / NASA / Commercial Crew 2. Steve Wofford / NASA / SLS Liquid Engine Office 3 Jack Fjeld / AFSPC / SMC / LRE
1035 - 1100	*Full Break*	
1100 - 1200	**Materials** Characterization, Variability, & Feedstock Control	1. Jeff Haynes /Aerojet Rocketdyne 2. Alex McCloskey / Northrop Grumman 3. Walter Roy/ DARPA
1200-1330	*Lunch Break*	
1330 - 1430	**Process Controls** Machine Parameters, Variability, Thermal History	1. Shane Gardner / LM Space Systems Denver 2. Shane Collins / CalRAM/Midstate Berkshire 3. Brian Hughitt / NASA / OSMA
1430 - 1435	*Transition to Other Tutorials/Workshops*	
1435 - 1535	**Quality and Inspection** NDE, Acceptance Criteria, Vendor Qualification	1. GE Representative 2. Kevin Klug / CTC – Concurrent Technologies 3. Eric Burke / NASA / LaRC
1535 - 1605	*Full Break*	
1605 - 1705	**Panel Discussions** **Panel A**: Certification Process **Panel B**: Materials, Process Controls, Quality and Inspection	**Moderator:** Mary Kinsella **Panel A:** Rick Russell, Steve Wofford, Jack Fjeld **Panel B:** Shane Gardner; Jeff Haynes; GE

Summary

- Must balance AM opportunities and risks

- Set requirements to allow innovation while managing risk

- Center-level AM requirements currently in draft
  - Will have wide-ranging review
  - Defines the expectations for engineering and quality control in developing critical AM parts

- Need Agency level cooperative effort to help close knowledge gaps in certification requirements to better manage AM risk